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A model of the Cygnus X-3 system in the gamma-rays region

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Abstract. — We propose the model to explain the Cyg X-3 light curve in the TeV energy region. In our model very high energy (VHE) gamma rays are produced near the compact object by photoproduction process and photodisintegration of nuclei (deexcitation of nuclear fragments with large Lorentz factors). In low mass binary systems containing a compact object VHE gamma rays interact with soft photons around the companion star by $\gamma\gamma \rightarrow$ee reactions. These soft photons have a radial distribution, so the VHE gamma rays will be observed when their source lies between the companion star and the observer, as the reaction is impossible if the angle between the momenta of the soft photon and of the gamma quantum is small. In this model the VHE gamma rays ligth curve has a sharp maximum in the orbital phase region 0.2 - 0.8 depending on the orientation and eccentricity of the orbit. Our calculations show that for Cygnus X-3 orbital parameters the light curve maximum lies at phase $\simeq 0.6$, in agreement with recent observational data. In the model the non-periodic variability and redistribution of VHE gamma rays will be caused by variations of soft photons coming from the companion star. Simultaneous EGRET and ground-based observations will permit to check the predictions of our model.

Key words: VHE gamma-rays, close binaries, light curve, Cygnus X-3.

1. Introduction.

The unusual properties of the X-ray binary system (4.8h period) Cygnus X-3 has been the subject of interest in a large number of papers during the last years (e.g., see review papers of Bonnet-Bidaud & Chardin 1988; Protheroe 1987). All existent models connect the generation of the VHE/UHE γ-radiation with the π^o production by a particle beam, accelerated by the compact object, in the companion star atmosphere (e.g., Vestrand & Eichler 1982; Kazanas & Ellison 1986; Berezinsky 1987) or in accreting matter near the object (Protheroe & Stanev 1987; Hillas 1984). The observed modulation of 4.8h has most probably an orbital nature, but orbital models which assume VHE γ-rays generation in the companion's atmosphere have a lot of difficulties. It is easy to explain in these models γ-pulses at the phase regions $\approx$.0.2 and or $\approx$0.8, but the origin of the maximum at the phase $\approx$0.6 as observed (Bonnet-Bidaud & Chardin 1988; Protheroe 1987) remains incomprehensible.

In Moskalenko *et al.* (1991) we have considered a model consisting of a close binary system, which contains a compact object and an ordinary hot companion star. The main assumption of our model is that VHE γ-rays are produced near the compact object (e.g., via π^o production as it has been discussed in papers of Protheroe & Stanev 1987 and Hillas 1984, and via photodisintegration of nuclei: Karakula *et al.* 1991). In such a system the produced VHE γ-rays interact with soft photons around the companion star by $\gamma\gamma \rightarrow$ee reactions. These soft photons have a radial distribution, so the VHE γ-rays will come to observer when the VHE γ-rays source lies between the companion star and the observer, because if the angle between the momenta of soft photon and γ-quantum is small or equal to zero the reaction is impossible. In this model the VHE γ-rays light curve has a sharp maximum in the orbital phase region 0.2 to 0.8 depending on the orientation and eccentricity of the orbit. The considered model is applied to Cygnus X-3.

2. Description of the model.

The main assumption of our model (Moskalenko *et al.* 1991) is that VHE γ-rays are produced near the compact object: their modulation results from their absorption on the radial photon field of the companion star.

The angular distribution of soft photons from the companion star at the point A (Fig. 1a) is approximated by a radial dependence as a δ-function, we choose the Z axis in the observer's direction and get:

$$N(\varepsilon, \cos\theta, d) = n(\varepsilon)\frac{R_S^2\delta(\cos\theta - \cos\alpha)}{2d^2}, \quad (1)$$

where ε is the energy of soft photon, θ is the angle between the momentum of the soft photon and Z axis, $n(\varepsilon)$ is the number density of soft photons with energy ε at the companion star surface; the angle α is shown in Figure 1a, R_S is the companion star radius and d is the distance from the point A to the companion star. The constant 1/2 in the formula (1) comes from the fact that half of the photons have momenta outwards of the companion's surface.

The VHE γ-rays flux at the observer position is:

$$I_{obs}(E_\gamma) = I_o(E_\gamma)\,\exp(-K(E_\gamma)), \quad (3)$$

where $I_o(E_\gamma)$ is the flux from the compact object, the attenuation coefficient $K(E_\gamma)$ is given by:

$$K(E_\gamma) = \int_0^\infty \frac{dl}{\lambda(E_\gamma, \alpha, d)} \quad (4)$$

$\lambda(E_\gamma, \alpha, d)$ being the mean free path length of γ-quanta for the (e^+e^-) process at the point A. In this formula the integration over ℓ takes place along the line of sight (Z axis) from the compact object to the observer.

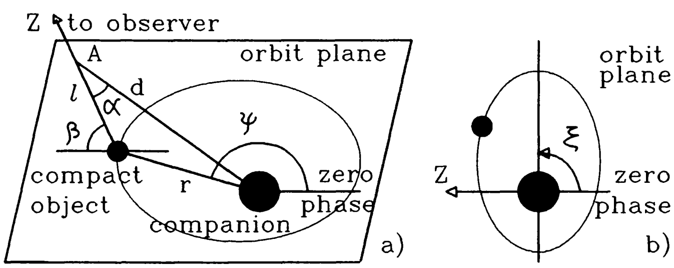

FIGURE 1. The geometry of a close binary system.

observations in this energy range are clustered around $\varphi \approx$ 0.6−0.7. The approximate agreement in phase of emission in all the last reported observations is very striking and gives, evidence that VHE/UHE γ-rays are indeed emitted by Cygnus X-3.

It is easy to explain by interaction with companion's atmosphere models γ-pulses at the phase regions $\approx$ 0.2 and/or $\approx$ 0.8, but the origin of maximum at the phase $\approx$ 0.6, as observed for Cygnus X-3 system during the last years (Bonnet-Bidaud & Chardin 1988; Protheroe 1987, remained unexplained. The phase $\varphi \approx 0.6$ corresponds to the position of the compact object between the companion and the observer.

We have used our model (Moskalenko et al. 1991) for explaining VHE γ-ray light curve of Cygnus X-3. In Figure 2 the calculated phase-dependence of 1 TeV γ-rays flux from Cygnus X-3 is shown (Eq. 3 of this paper, $I_o = 1$). The following values of the parameters have been assumed: eccentricity $e = 0.45$, companion star radius $R_S = 10^{11}$ cm, semi major axis of the orbit $a = 2 \times 10^{11}$ cm, temperature of black-body photons field $kT = 4$ eV. The curves are drawn for inclination angles $i = 50°, 70°, 90°$, and for orbit orientation angles $\xi = 30°$ (solid line) and $\xi = 90°$ (dotted line). It is seen that for $\xi = 90°$ and various values of inclination angles the maximum is at phase $\varphi \approx 0.8$. The position of maximum changes to $\varphi \approx 0.6$ when the orbit orientation angle decreases to $\xi = 30°$. The sharpest maximum is seen when the inclination angle i is 90°, because it is only for $i = 90°$ that the absorption of VHE γ-rays is neglected when $\psi = 180°$ (the compact object being in front of companion star). As the inclination angle decreases the angle between the momenta of the γ-quanta and the soft photons increases. So the amplitude of the light curve maximum decreases due to increasing of the possibility of $\gamma\gamma \rightarrow$ee reactions.

3. The light curve of Cygnus X-3.

Cygnus X-3 is a close X-ray binary system in which the X-ray emission is modulated by a 4.8h period, generally assumed to be the orbital period. The distance between its components is estimated of a few times 10^{11} cm. The object has not been seen at optical wavelengths due in part to its location in the galactic plane at a distance more than 10 kpc from the Sun. Cygnus X-3 has been seen at several other wavelengths: radio, infrared, and VHE and UHE γ-rays (Bonnet-Bidaud & Chardin 1988). No new results of VHE observations of this source have been published recently. The information on orbital phase of γ-ray emission at TeV and PeV energy regions reported before 1987 is summarized by Protheroe (1987). While the early observations (pre-1980) indicate VHE γ-emission at phases $\varphi \approx$ 0.1−0.2 and $\varphi \approx$ 0.7−0.8, all the later

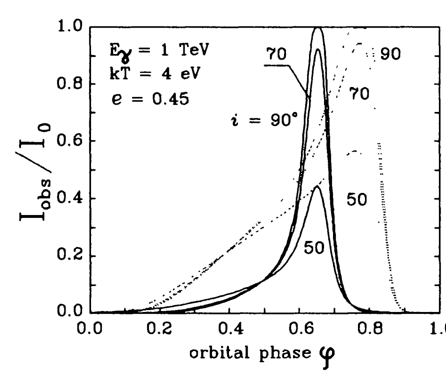

FIGURE 2. The light curve of the Cygnus X-3 system, calculated for: γ-ray energy E_γ = 1 TeV, eccentricity e = 0.45, temperature of photon field $kT = 4$ eV and for different values of the inclination angle i. The Solid line corresponds to the orbit orientation angle $\xi = 30°$, the dotted line to $\xi = 90°$.

In Figure 3 light curves for γ-rays energies $E_\gamma = 0.1, 1$ and 10 TeV are shown ($I_o = 1$). The curves are drawn for an inclination angle $i = 70°$ and for an orbit orientation angle $\xi = 30°$, other parameters being the same as in Figure 2. It is seen that the maximum of the light curve lies at the same phase for various energies, but that the shapes of the light curves are different. This effect is the result of the energy dependence of attenuation coefficient.

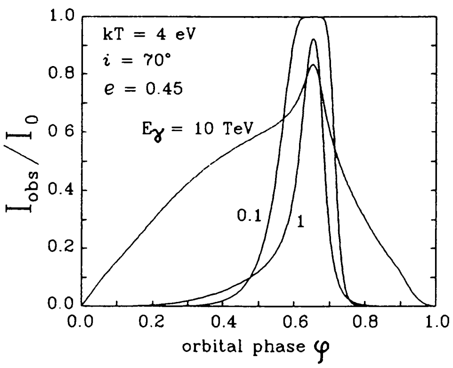

FIGURE 3. The light curves for an inclination angle $i = 70°$, an orbit orientation angle $\xi = 30°$ and several values of γ-rays energies. The other parameters are the same as for Figure 2.

4. Discussion and conclusions.

There are some consequences of our model for Cygnus X-3 system:

- the transition of the VHE γ-pulse from the phase ≈ 0.8 to the phase ≈ 0.6, observed at the beginning of 1980's (Protheroe 1987), may be connected with precession of the elliptical orbit of the compact object (as shown in Fig. 2). The period of the precession is estimated as ≈ 60 years;
- the eccentricity of the orbit e in this case must be greater than or equal to ≈ 0.4, in agreement with other calculations (Gosh *et al.* 1981; Giler 1989);
- the position of the γ-rays pulse in our model should be around the X-ray maximum position (but not necessary in coincidence);
- the peak at phase ≈ 0.2, observed by several groups (Protheroe 1987), is impossible to understand in our model, because the X-ray maximum lies between phases 0.6 and 0.8 (Willingale *et al.* 1985). Therefore this peak may be the result of other mechanisms;
- the absence of significant VHE γ-emission at present may be connected with increasing activity of the companion star, so the VHE γ-radiation is fully absorbed;
- the absorption of VHE γ-radiation (by the $\gamma\gamma \to$ ee process) could give an increase of the HE γ-radiation in the GeV energy range. This increase is the result of an electromagnetic cascade from the primary VHE γ-quanta. Such a cascade takes place also when the phase of the compact object differs from the phase of VHE γ-ray maximum, thus the shape of HE γ-ray light curve should differ strongly from the X-ray and VHE γ-ray ones (two maxima and/or a changing phase of maximum are possible in the HE region). However, from the accurate calculation of the cascade photon spectra and its time correlation, measurements by Cherenkov telescopes (TeV) and EGRET (HE) should allow to test our model.

References

Berezinsky V.S. Proc. 20th Int. Cosmic Ray Conf., 1987, v.9, p. 39

Bonnet-Bidaud J.M., Chardin G. Phys. Rep., 1988, v.170, p. 325

Giler M. Proc. Int. Workshop on Very High Energy Gamma Ray Astronomy, Eds. by Stepanian A.A. *et al.*, Crimea 1989, p. 91

Gosh P. *et al.*, 1991 ApJ, v. 251, p. 230

Hillas A.M. 1984 Nat, v. 312, p. 50

Karakula S., Kociolek G., Moskalenko I.V., Tkaczyk W. 22nd Int. Cosmic Ray Conf., 1991, v. 1, p. 536

Kazanas D., Ellison D.C. 1986 Nat, v. 319, p. 380

Moskalenko I.V., Karakula S., Tkaczyk W. Proc. 22nd Int. Cosmic Ray Conf., 1991, v. 1, p. 544

Protheroe R.J. Proc. 20th Int. Cosmic Ray Conf., 1987, v. 8, p. 21

Protheroe R.J., Stanev T. Proc. 20th Int. Cosmic Ray Conf., 1987, v. 1, p. 254

Vestrand W.T., Eichler D., 1982 ApJ, v. 261, p. 251

Willingale R. *et al.*, 1985 MNRAS, v. 215, p. 295